Rodent outbreaks in Australia: mouse plagues in cereal crops

Peter R. Brown, Grant R. Singleton, Roger P. Pech, Lyn A. Hinds, and Charles J. Krebs

Mouse plagues have been a feature in cereal cropping areas in southeastern Australia for more than 100 years. Mouse plagues occur in response to a series of environmental conditions such that the population abundance increases from <1 mouse ha^{-1} to >1,000 mice ha^{-1} over a period of 12–18 months. Mouse plagues develop in response to factors such as weather, rainfall, food supply, predation, disease, and social structure. In general, each factor alone is not sufficient to generate or trigger a mouse plague, but each is necessary. High densities of mice can cause significant damage to crops, but they also have other impacts on rural communities. Research work has focused on understanding the mechanisms that lead to population increases and developing predictive models. These models can achieve 70% accuracy. A range of control options are available to farmers to manage high mouse population densities, which can be successfully implemented if farmers have some warning that high mouse population numbers are expected.

A mouse plague occurs somewhere in Australia once every four years, but on average it is likely to be one year in seven for any particular region (Singleton 1989, Redhead and Singleton 1988, Mutze 1991, Singleton et al 2005). These plagues of house mice, *Mus domesticus*, are a significant problem to agricultural areas of Australia. It has been conservatively estimated from a survey of grain-growers in Victoria and South Australia that the 1993 mouse plague cost AU$64.5 million (Caughley et al 1994). Within the wheat belt of southern and eastern Australia, a number of regions are defined by different soil types, cropping systems, and climate. Yet, each is subject to mouse plagues (Fig. 1). On the Darling Downs in southern Queensland, for example, winter and summer crops are grown on a continuous basis on self-mulching dark clay soils, whereas, on the light sandy loam soils of the Victorian Mallee, winter cereals are grown in the same paddock only once every 2–3 years. The mechanisms of plague formation in these regions differ markedly (see Singleton 1989, Cantrill 1992, Pech et al 1999). Curiously, widespread mouse plagues do not occur in Western Australia, although localized outbreaks occur (Plomley 1972, Chapman 1981). In 2003, high densities of mice were recorded for the first time in Tasmania, where they caused some damage to winter cereal crops and farmers used rodenticides to limit damage (M. Statham, personal communication).

It is generally believed that house mice were introduced to Australia with European settlers (Singleton and Redhead 1990, Redhead et al 1991). There have likely been numerous introductions to different localities around Australia and to some of

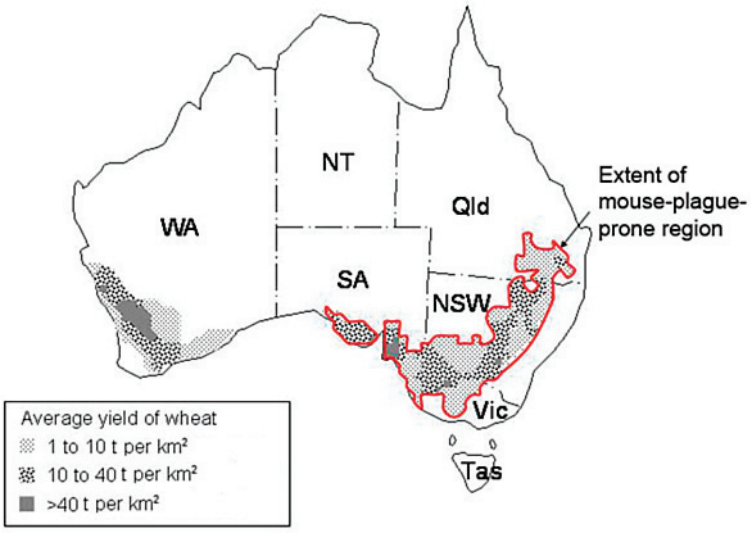

Fig. 1. Distribution of the major cereal production areas in Australia and extent of the region subject to periodic mouse plagues (enclosed by the solid line). Different levels of shading represent average yield of cereal crops (after Australian Bureau of Statistics 2003).

the offshore islands. Recent introductions of house mouse onto Thevenard Island, off the Western Australian coast, in the late 1980s have been well documented cases (Moro 2001). The house mice present in Australia would most likely have come from England, the Netherlands, or France and would therefore probably be *Mus domesticus* (= *Mus musculus domesticus*) rather than *Mus musculus musculus* (which occurs further west in Europe) (Sage et al 1993, Payseur and Nachman 2005). Domestic and feral populations of house mice have done extraordinarily well in Australia by inhabiting almost all available ecological niches. They have done particularly well in highly modified agricultural landscapes, where native rodents have faired poorly (Redhead et al 1991). There have been reports of population outbreaks in some native rodent species; however, these mostly occur after favorable climatic conditions in the arid interior of Australia (Newsome and Corbett 1975, Masters 1993, Predavec and Dickman 1994, Dickman 1999). Feral house mice have exploited the highly modified agricultural environments to occasionally reach high densities and to cause significant crop damage and losses. In Australia, mice have had the advantage of not having specific predators (although a broad range of predatory birds, mammals, and reptiles feed on mice), no small mammal competitors in the crop ecosystems, and they do not have the full suite of diseases that their forebears have back in Europe (Singleton and Redhead 1990, Tattersall et al 1994, Singleton et al 2005).

Densities of mice in nonplague years are normally <50 mice ha^{-1}, sometimes as low as <1 mouse ha^{-1}, but, at peak densities during mouse plagues, densities can

exceed 1,000 mice ha^{-1} (Singleton et al 2001, 2005), a 200-fold change in density (see Korpimäki et al 2004 for discussion). The maximum density that has been estimated in crops was 2,716 mice ha^{-1} (Saunders and Robards 1983). Densities of mice can also be exceptionally high around intensive animal husbandry facilities such as piggeries during mouse plagues (Singleton et al 2007).

In southern Australia, the interval from a plague "trigger" to peak population densities is 12–18 months (Singleton 1989). However, at a macro-geographic scale, variation is high in the synchrony of outbreaks or plagues of mice in Australia. In some years, plagues occur from South Australia, through the grain belt of southern and eastern Australia, up to the Darling Downs in Queensland (a range of 1,500 km), whereas, in other years, they occur in smaller, localized areas (<50 km).

The purpose of this chapter is to review what is known of mouse plagues in Australia, what impact they have, why they develop, and what can be done to try to manage them.

The impact of mouse outbreaks on agricultural production

The crop that suffers the most from mouse plagues in Australia is wheat (Redhead and Singleton 1988, Brown and Singleton 2002). It is the main winter cereal crop grown in southern and eastern Australia, accounting for 70% of the grain export market, and it was worth US$4.2 billion in 2008-09 (www.abareconomics.com/interactive/AusWheat/ and www.abareconomics.com/interactive/08ac_march/excel/table_25a.xls, accessed 22 July 2010) (Fig. 1). Other crops that have experienced high losses during a mouse population eruption are barley, sorghum, maize, and soybeans. Pig and poultry production can also be affected severely. Caughley et al (1994) provide the most systematic assessment of the impact of a mouse plague in southern Australia.

Mice generally construct burrows in the undisturbed habitats adjacent to crops, such as along fence lines. When conditions are favorable, mice move into crops and build burrows once cover is sufficient (Singleton and Redhead 1990, Krebs et al 1995, Chambers et al 1996, 2000, Ylönen et al 2002).

Mice cause damage to crops by consuming grain and plant material. They damage crops by digging out newly planted seeds or germinating seeds (Mutze 1998, Brown et al 2003). Mouse populations generally peak in abundance at the time of sowing of winter cereals in southeastern Australia, and, during mouse plagues, farmers often have to re-sow their crops because mice have dug up the seed (Mutze 1998, Brown and Singleton 2002). Significant damage can occur at later stages of crop growth, particularly after mice begin breeding in early spring (Singleton et al 2001) and their numbers increase.

The ontogeny of house mouse outbreaks

House mouse outbreaks in Australia have been the subject of several detailed field studies and experiments that have attempted to describe and interpret the sequences of events that lead to an outbreak (Brown and Singleton 1999, Singleton et al 2005).

Figure 2 illustrates the factors that are potential causes of demographic release in house mice. We will summarize here the role each of these factors plays in generating an outbreak.

Weather

The earliest papers on outbreaks showed that drought-breaking rains were often a trigger for a mouse outbreak, but Brown and Singleton (1999) showed that there were two population states, such that in some years house mice responded rapidly to rainfall but in other years no response occurred. Good winter rainfall may thus be necessary for an outbreak to occur but it is not sufficient. By contrast, droughts are sufficient to prevent an outbreak.

Food supply

Rainfall is a surrogate for food supply in mice, and without question food is essential for mouse reproduction and survival. The puzzle, however, is that a feeding experiment on low-density populations of mice did not trigger an outbreak (Jacob et al 2007, Ylönen et al 2003). A similar experiment adding water to a summer mouse population produced no population gain (Brown et al 2008). Again, we conclude that high-quality food is necessary for an outbreak but not sufficient.

Predation

Predators can limit mouse numbers when densities are very low and when predators can aggregate in high numbers (Sinclair et al 1990) but they cannot make any headway on rapidly growing populations because the rate of increase of mice is so high (Brown and Singleton 1999). However, the risk of predation can affect body growth

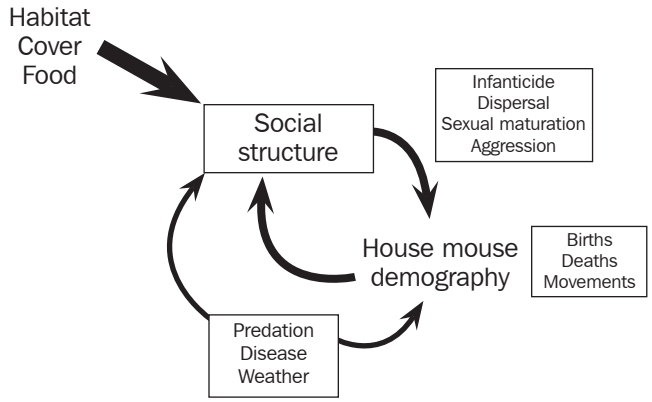

Fig. 2. Factors potentially affecting the rate of increase of house mice in south-eastern Australia. The thicker the line, the larger the likely effect of the factors (after Singleton et al 2007).

rates of mice (Arthur et al 2004), and hence their maturation. Therefore, the direct and indirect effects of predation need to be investigated at the stage of low mouse numbers, when it is most difficult to carry out such a study. Thus, predation remains an untested possibility for the phase of low density.

Disease

Although diseases can be found in high-density house mouse populations, they appear to result from high contact rates and thus are an outcome of high density (Singleton et al 1993). Diseases, such as mouse parvovirus, can be inferred to be significant in precipitating the decline phase of an outbreak when densities are dropping too rapidly to suspect any other cause (Singleton et al 2000). As such, disease is probably aggravated by food shortages that start to occur after cereal crops are harvested in summer and the accumulation and circulation of different diseases through high-density populations. Thus, disease may be a contributing cause to the decline of an outbreak but the absence of disease does not appear to explain why an outbreak is triggered.

Social structure

Social interactions have the potential to affect rates of population increase through infanticide, direct aggression, and induced dispersal. In addition, social interactions affect the timing of sexual maturation in young mice (Drickamer 1984, Oli and Dobson 1999). We have no direct studies of any of these processes in wild house mouse populations, and consequently cannot draw any direct conclusions.

The best insight we have into social structure came from an elegant study by Sutherland and Singleton (2006). By monitoring the activity of individuals with event recorders in the field, they showed that house mice switch between two different social systems—an almost asocial structure at low densities and a territorial system as abundance increases. This could be a function of the relatedness of individuals and an adaptation to prevent infanticide at high mouse densities. Adult females appeared more likely than males or juveniles to make the significant social shift. The trigger for this change remains unclear and further studies are needed to determine the mechanism of this social shift.

The importance of this work by Sutherland and Singleton (2006) is that it now provides a second process in a comprehensive two-factor model to explain mouse outbreaks. Not only is a good food supply needed, provided by good rains, but the social structure of the population must also be such that it can switch to a territorial system. Without this social switch, good rainfall does not lead to a mouse outbreak. This model is in need of further testing, particularly because we have few data on both the social component of the model and the food component (e.g., are ripening and germinating seeds—White 2002—and insects critical food items in spring when an outbreak begins?). We hope that this model will give insight into the biological curio of house mouse outbreaks aptly described by Singleton et al (2005) and help lead to effective control measures to prevent crop damage.

Predictive models for mouse outbreaks

Models for outbreaks of house mice have been developed at a regional scale for New South Wales (NSW), Victoria, and South Australia, and at the local or district scale from detailed monitoring and experimental studies (Pech et al 1999). All the regional models assume that climatic factors are the primary drivers, or at least precursors, to outbreaks, whereas localized studies included factors such as soil structure (Newsome 1969a,b), food quality (Redhead et al 1985), predation (Sinclair et al 1990), refuge habitat (Singleton 1989), and crop type (Twigg and Kay 1994). The most recent models are either quantitative, that is, using the rate of increase to predict seasonal changes in abundance (Pech et al 1999), or qualitative, that is, generating estimates of the probability of occurrence of an outbreak (Kenney et al 2003, Stenseth et al 2003, Davis et al 2004), based on combinations of rainfall data and spring trapping data. Although useful models have been developed for the rate of population decline over winter and the rate of increase over summer (Stenseth et al 2003), the main shortfall with the quantitative approach is that a model for the duration of the breeding season remains elusive (Pech et al 2003). Most likely, the two-factor model described above is needed to fill this gap. The qualitative models are simple to run (Appendix A, at www.scribd.com/doc/3837203). Using data available in spring, they achieve 70% correct predictions of whether or not an outbreak will develop over the subsequent summer (Kenney et al 2003).

Given that models can be used to predict the probability of an outbreak, when should farmers intervene with preemptive control? The threshold probability for intervention depends on the balance between the costs of control and savings in reduced damage to crops (Davis et al 2004). Based on 2004 market values for crops and rodenticides, the optimal long-term strategy for farmers is to apply preemptive control when the probability of an outbreak is ≥ 0.3. Managers who take the risk of never applying preemptive control and highly risk-averse managers who apply control every year would be substantially worse off than risk-neutral managers who respond at this threshold. In northwest Victoria, the threshold probability corresponds to rainfall of approximately 280 mm over the period from April to October (Davis et al 2004), or more generally for southern Australia the probability of an outbreak can be estimated using the models in Appendix A (at www.scribd.com/doc/3837203).

The success and failures of management actions

A range of control strategies have been tried against mice in fields over the years. Broadly, these have included trapping, poisons, and habitat modifications.

Trapping

Traps are normally used in and around houses and storage sheds, and can also be used in the field, but, because of the high rates of re-invasion, they are rarely used. Farmers have been known to use all sorts of ingenious home-made traps or commercial traps to try to reduce mouse numbers in their fields. A classic example as used in rural

Victoria in 1917 was an intricate design of metal guard fencing to channel mice into a pit, where hundreds of thousands of mice were captured in a few nights (Fig. 3). Another type of trap used by farmers is to position a greasy bottle over the edge of a large bucket filled with water. Mice climb up onto the bottle to reach some attractive food stuck in the end of the bottle, but slip into the water and drown. The problem with all these traps is that they take a lot of effort to set them, they can catch only a small number of animals, and they are used only when numbers are already very high and damage has occurred.

Poisons

A range of registered and unregistered rodenticides have been used to try to control damage caused by mice to crops. Since the late 1990s, zinc phosphide has been registered in Australia as an in-crop rodenticide. It is commercially produced and the rodenticide is coated on the outside of sterilized wheat grains. It can be spread into growing wheat crops using a calibrated standard fertilizer spreader or applied aerially by light planes. Prior to zinc phosphide being registered, strychnine had temporary registration for use during mouse plagues. It was used heavily during the 1993-94 mouse plague in South Australia and Victoria, where 350,000 ha were baited. There was evidence that the strychnine could be taken up into the plant under certain soil conditions and this led to it being banned for broad-scale use in the field. Zinc phosphide and strychnine are "acute" rodenticides that act relatively quickly.

Fig. 3. Some 500,000 mice were captured around stores of wheat in just 4 nights during a mouse plague in northwestern Victoria, Australia, in 1917.

Zinc phosphide can reduce mouse populations by 40–98% (Mutze and Sinclair 2004, Brown 2006). However, it is often applied after damage has already occurred, and, during mouse plagues, high mouse numbers often undergo natural crashes anyway (Brown 2006). The use of zinc phosphide remains the cheapest and easiest form of broad-scale mouse control.

Second-generation anti-coagulant rodenticides such as bromadiolone and brodifacoum have been registered in some states for use around the perimeter of crops but not in-crop.

Habitat modification

A range of farm management/cultural practices have been tested in Australia to reduce the impact of mice on crops. These practices include mowing margins of crops, harrowing, plowing, grazing, application of herbicides, and provision of alternative low-value food at the periphery of high-value crops at key times. Two field studies were conducted to test the effectiveness of some of these practices. The first was conducted in Victoria and showed that reducing the amount of grasses and weeds in noncrop habitats subsequently reduced the number of mice in adjacent crops (Brown et al 1998). The second experiment was conducted in irrigated crops in NSW and showed that, by applying a combination of practices, including spraying weeds and grazing by sheep, a significant reduction occurred in grass biomass, which subsequently reduced mouse abundance (Brown et al 2004). Yields of winter cereals and rice were 40% higher after treatment. The recommendations from this experiment are provided in Table 1.

Another practice that has been tested was to sow wheat crops deeper. A field experiment demonstrated that fewer mouse holes were observed when wheat was planted at 50 and 70 mm compared with a sowing depth of 30 mm (Brown et al 2003).

Fertility control

An alternative approach to lethal control is to reduce the recruitment of young mice into the population by affecting the fertility of adult females. A review of approaches to fertility control for small mammals is presented elsewhere in this volume (Singleton et al). For house mice, there has been a large research effort to develop fertility control of female mice using immunoncontraception (Chambers et al 1999). The objective was to sterilize female mice using a mouse reproductive protein that generated an immune response, such that the antibodies blocked development of the egg in the ovary or inhibited its fertilization in the reproductive tract. This reproductive antigen was to be delivered using a mouse-specific disseminating virus (Tyndale-Biscoe 1991, Shellam 1994, Tyndale-Biscoe and Hinds 2007). Proof of concept was achieved in laboratory colonies of house mice using a recombinant murine cytomegalovirus (MCMV) that expressed the egg coat protein, mouse zona pellucida 3 (ZP3). All infected mice became infertile for periods greater than 250 days (Lloyd et al 2003). However, the method was never field-tested because, in wild mice, raised under laboratory conditions, transmission of the recombinant virus to naïve mice was very poor (Redwood et al 2007). Although some public concerns were raised regarding the release of such a

Table 1. List of recommended farming practices to reduce the impact of mice in the irrigated summer cropping area of southern New South Wales (modified from Brown et al 2004).

Action	Level of action	Timing of action	Other benefits	Practicality	Priority	Likelihood of success
Summer crop						
Cultivate early	Routine	May-September, before winter	*Heliothis* control	High	High	Medium
Control weeds/remove food and cover/spray	Routine	Twice (spray) early and follow up	Control disease, reduce soil seed bank, farm hygiene	Medium	High	High
Winter crop						
Presowing stubble management—burn	If numbers high	Depends on weather	Rubbish removal	Medium	Medium	High
Presowing stubble management—incorporate	Routine	As early as possible	Breakdown of nutrients	Medium	Medium	High
Control weeds	Routine	Before spring	Control disease, reduce soil seed bank, farm hygiene	Medium	Medium	High
Sow deeper	Not a priority	At sowing	Clean up and bait rather than adjust rate	Low	Low	Low
Increase sowing rate	Not a priority	At sowing	or depth	Low	Low	Medium
Monitor mice	Routine	Presowing	As above			
			See mouse activity	Low	High	High
Perimeter bait	If numbers high	Pre- or at sowing	–	Low	High	Medium
Rice crop						
Stubble management—slash early	Routine	Soon after harvest	Weed control	Low	Low	Medium
Stubble management—graze	Routine	Soon after harvest	Weed control	Medium	Low	High
Stubble management—burn early	?	After harvest	Weed control	Medium	Low	High
Stubble management—burn later	?	Following spring	Weed control	Medium	Low	Medium
Manage channels and banks	Routine	Ongoing	Control disease, reduce soil seed bank, farm hygiene	Low	High	High
Bait stations	If numbers high	Before breeding season	–	Low	Medium	Medium
Other actions						
Sow early (all crops—on time)	Routine	Depends on rainfall	–	Low	Low	Low
Harvest cleanly (all crops)	Routine	At harvest	Economic gains	Low	High	High
Remove and reduce cover around sheds, silos	Routine	Continuous	Keeps farm clean	Low	Medium	High
Monitor for signs of mouse activity	Routine	Key times (early spring and autumn)	–	Low	High	High
Clean up grain spills (silos, field bins)	Routine	Sowing and harvest	Economic gains	Low	High	High
Mouse-proof houses, grain, stock feed storages	If numbers high	Continuous	Initial high cost	Low	Medium	Medium
Bait key habitats using bait stations	If numbers high	Before spring	–	Low	High	High

genetically modified organism (Fisher et al 2007), if funding becomes available in the future, the potential of this recombinant MCMV as a nondisseminating oral product could be assessed or a different virus vector could be developed.

Lessons learned

Over the last 30 years, we have made significant progress toward understanding the population dynamics of feral house mice and the factors that contribute to house mouse outbreaks and mouse plagues. Mouse plagues develop in response to factors such as weather, rainfall, food supply, predation, disease, and social structure. In general, each factor alone is not sufficient to generate or trigger a mouse outbreak or mouse plague, but each, in combination, is necessary.

Detailed knowledge about breeding dynamics and the relationship with mouse population dynamics and food supply and rainfall has been critical in understanding mouse population rates of increase and in developing models to predict outbreaks.

A range of management options are available to farmers; however, given the irregular nature of mouse plagues, it is hard to get farmers to implement preemptive management. Monitoring of mouse populations in key areas is needed to be able to adequately predict where and when outbreaks of mice will occur. However, monitoring over large areas requires a large investment in training and resources.

There needs to be a nationally coordinated approach to monitoring mouse populations so that action can be taken before mouse numbers have reached levels that lead to crop damage. However, few people with relevant skills remain in state or national government agencies. Effort is required to build and maintain this capacity; otherwise, large areas of crops will suffer significant mouse damage and inappropriate forms of management will be applied. For example, during a recent outbreak of mice, farmers were given advice from a state government department to mix insecticide baits for mice. This led to significant nontarget deaths of grain-feeding birds and secondary poisoning impacts. This should not occur when a registered product is commercially available and it is relatively cheap to administer.

Outbreaks of house mouse populations also occur in New Zealand, where work on mice has been done in substantially unmodified ecosystems. The focus in New Zealand is managing mouse populations to protect native fauna. The population increases in mice in New Zealand beech forests are small compared with the mouse plagues of Australia (see Ruscoe and Pech, this volume). The main lesson to learn from the comparison of outbreaks of mouse populations in Australia and New Zealand is that mice have an impressive physiological plasticity that enables them to extend their breeding season or to breed at different times of the year in response to pulses of food supply.

Conclusions

We have made good progress in understanding the mechanisms that generate outbreaks of mouse populations in Australia, and in developing predictive models that provide

sufficient time for farmers to implement ecologically based management practices in southern Australia. However, the grain industry or state governments need to instigate appropriate surveillance and population monitoring so that the models become operational.

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Notes

Authors' addresses: Peter R, Brown, CSIRO Ecosystem Sciences, GPO Box 284, Canberra, ACT 2601, Australia; Grant R. Singleton, International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines; Roger P. Pech, Landcare Research, PO Box 40, Lincoln 7640, New Zealand; Lyn A. Hinds, CSIRO Ecosystem Sciences, GPO Box 1700, Canberra, ACT 2601, Australia; Charles J. Krebs, Department of Zoology, University of British Columbia, 6270 University Boulevard, Vancouver, B.C. V6T 1Z4, Canada. Email: Peter.Brown@csiro.au.